



CMC Research at NASA Glenn in 2018: Recent Progress and Plans

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CMC Research at NASA Glenn

- CMC Development & Characterization
- Modeling & Validation
- Additive Manufacturing



CMC Development and Characterization

- **2700 °F CMC development**
- **Effects of engine environment
on CMC/EBC damage modes**

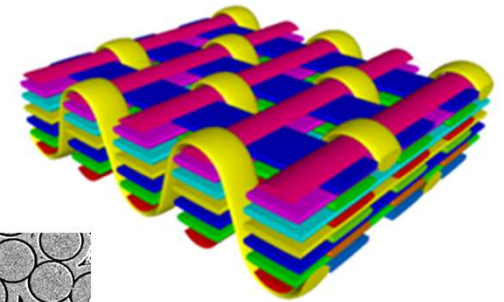


NASA 2700°F CMC combines three technology advancements

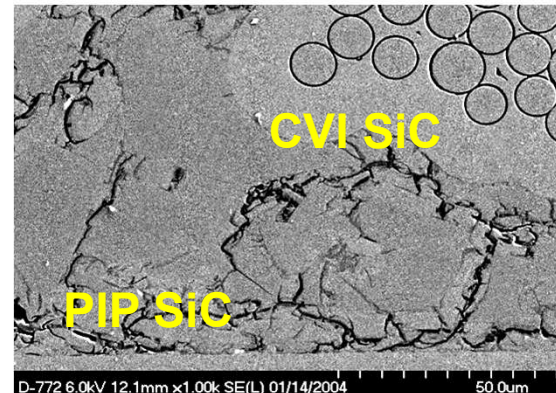
- **Creep-resistant Sylramic-iBN fiber**



- **Advanced 3D fiber architecture**



- **Hybrid CVI-PIP SiC matrix**





Creep and fatigue tests demonstrated durability of 3D hybrid-matrix CMC at 2700°F

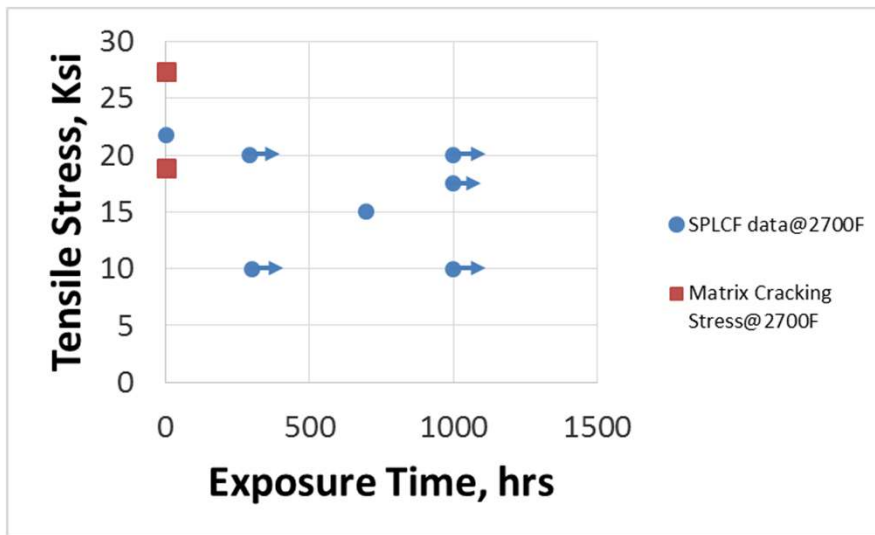
Challenge

Durable 2700°F Ceramic Matrix Composites will reduce cooling air required for turbine engine components, increasing engine efficiency and reducing fuel burn and emissions

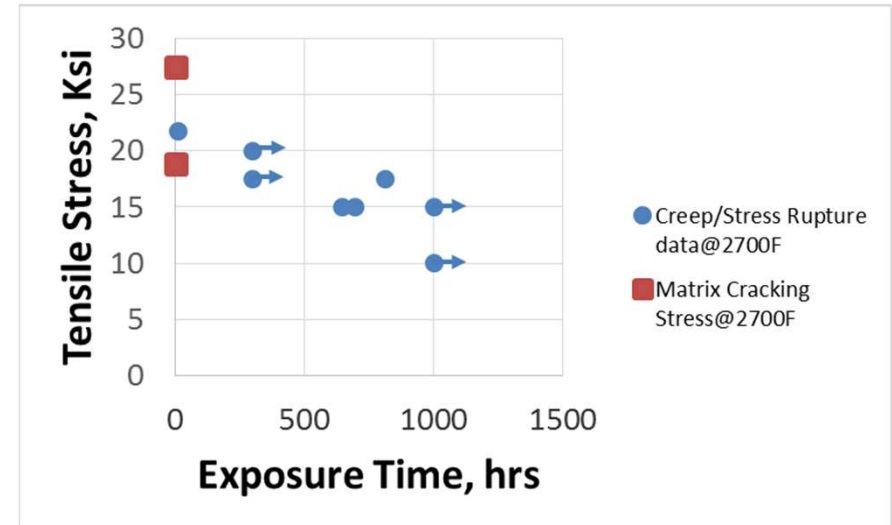
Approach

Characterize mechanical properties and durability of TTT-developed CMC at 2700°F

Fatigue (SPLCF)



Creep Rupture



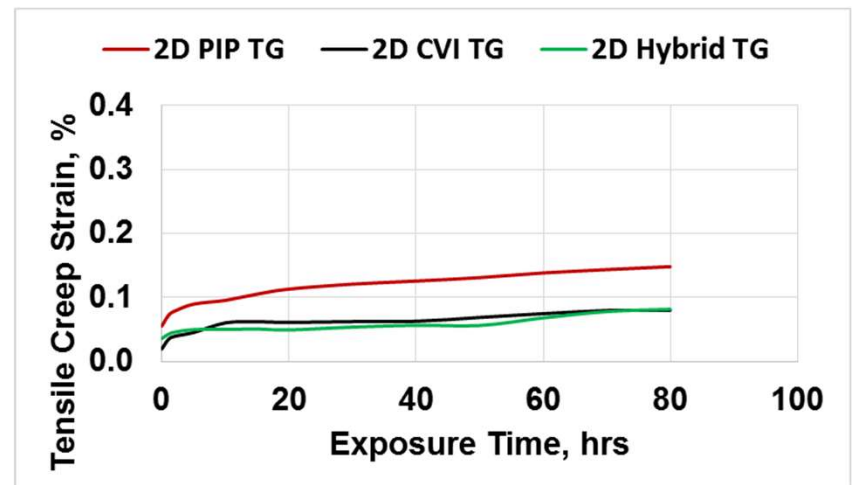
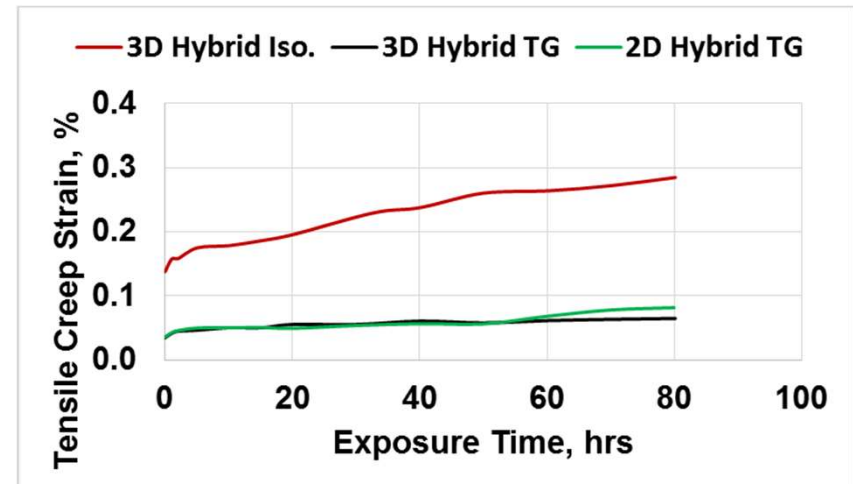
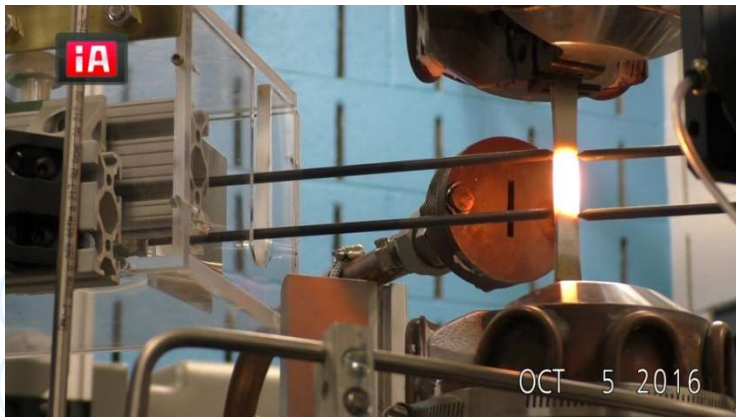
CMC shows 1000 hours durability at 2700°F and 15-20 ksi in creep and fatigue

Contact: Ramakrishna.T.Bhatt@nasa.gov



Effect of thermal gradients on creep strains of SiC/SiC CMCs evaluated at 2700 °F

- CMCs with 2D & 3D fiber architectures and CVI (2D only), PIP (2D only), and CVI/PIP hybrid matrices tested for 80 hours in creep at 10 ksi under isothermal & thermal gradient (TG) conditions (2700 °F max temp)
- Through-thickness TGs generated in uncoated SiC/SiC CMCs with laser heating and backside air cooling. Front and back side temp. measured with pyrometers and IR camera



Isothermal test on 3D hybrid CMC generated highest creep strain followed by TG test on 2D PIP matrix CMC. Uncoated CMCs sustained steady thermal gradients with a creep stress of 10 ksi for 80 hours without an EBC. Results of SPLCF tests generated on the same materials are being evaluated.

Contact: Sreeramesh.Kalluri-1@nasa.gov

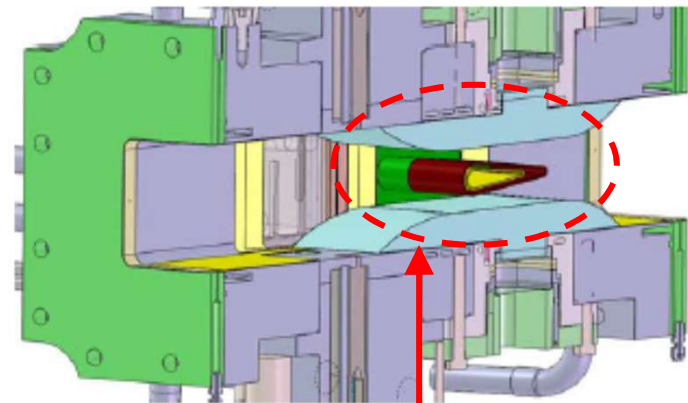


Rig test evaluation of CMC/EBC underway at UTRC

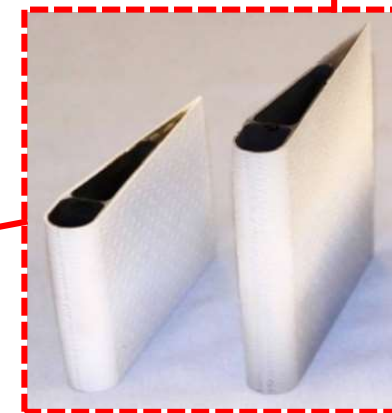
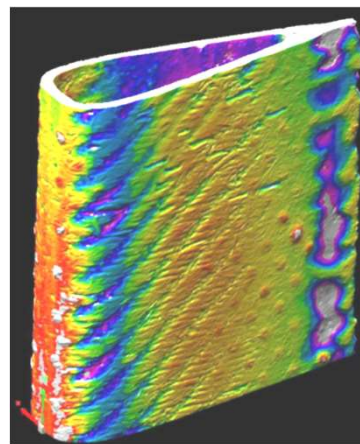
CMC subelement will be used to evaluate material capabilities in a simulated turbine environment

- 2700°F airfoil-shaped test article, 3x3 inches
- Mach No. $0.2 < M < 0.8$ in test section
- Rig shakedown complete, test program underway
- Thermocouples, pyrometers and IR camera monitor material temperatures
- NASA / P&W / UTRC collaboration

UTRC JBTS test rig



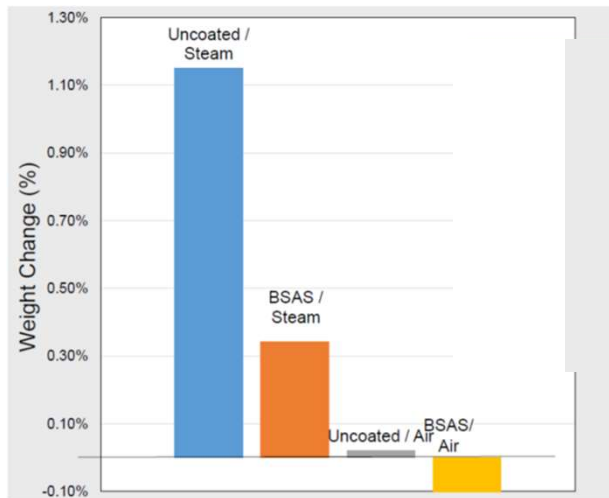
White light imaging shows surface variability of test article



airfoil subelements

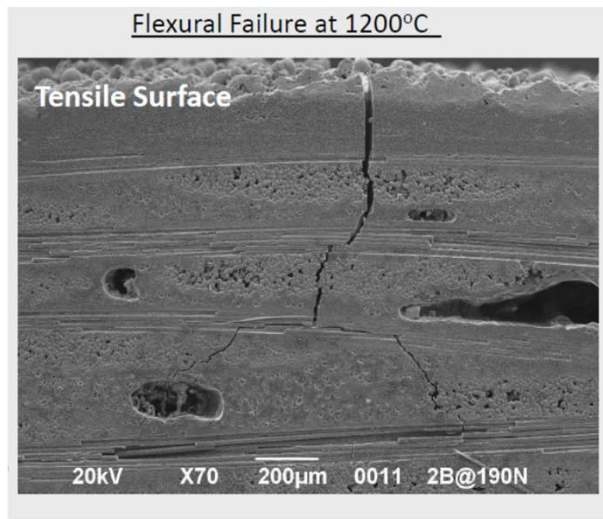


EBC slows damage accumulation at 2200°F in steam environment

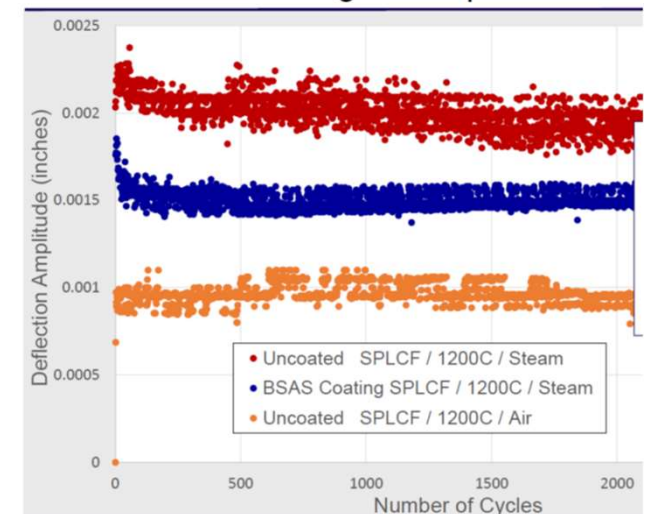


Flexural fatigue tests in steam show mechanics of damage propagation in EBC-coated CMC

EBC slows **weight gain** and **stiffness reduction** in CMC



Cracks initiate in EBC (in tension), propagate into CMC, and branch at ply interface



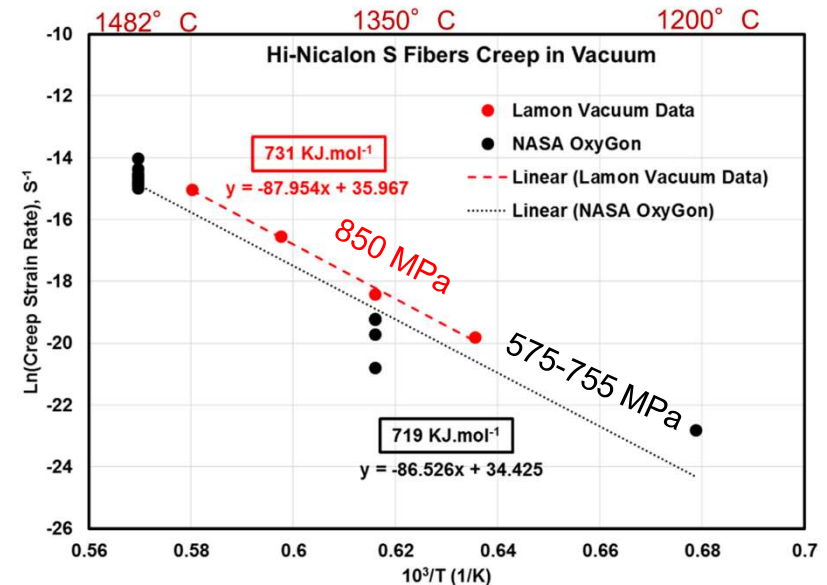
Change in amplitude with fatigue cycles



New lab measures environmental effect on fiber creep

Capability:

- New fiber characterization lab can conduct 3 simultaneous creep tests in Argon or vacuum up to 3000 °F.
- Inert environment simulates fiber behavior in un-cracked CMC



Creep Measurements validated with literature data

Characterization of creep damage in SiC fibers was used to obtain model parameters for life prediction in ceramic composites

Contact: Amjad.S.Almansour@nasa.gov

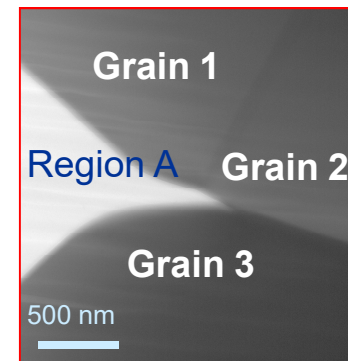
Development of CMAS-resistant EBCs



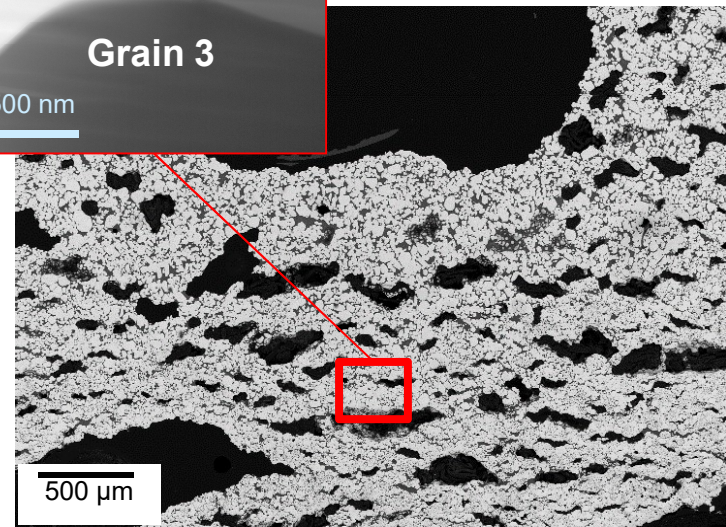
PROBLEM: Above 1100°C, molten calcium-magnesium-aluminosilicate (CMAS) can degrade environmental barrier coatings via thermochemical interactions, resulting in premature EBC failure

APPROACH:

- Understand causes of EBC degradation by characterizing thermochemical interactions of CMAS with ytterbium disilicate (YbDS) EBC
- Expose hot-pressed YbDS substrates to CMAS at 1200-1500°C for 1- 50 hour durations
- Evaluate CMAS/YbDS interactions using transmission electron microscopy (TEM), selected area diffraction (SAD) and energy dispersive spectroscopy (EDS) for microstructural and compositional analysis



TEM micrograph of region midway through CMAS-exposed YbDS substrate



CMAS/YbDS substrate after 1500°C-50h

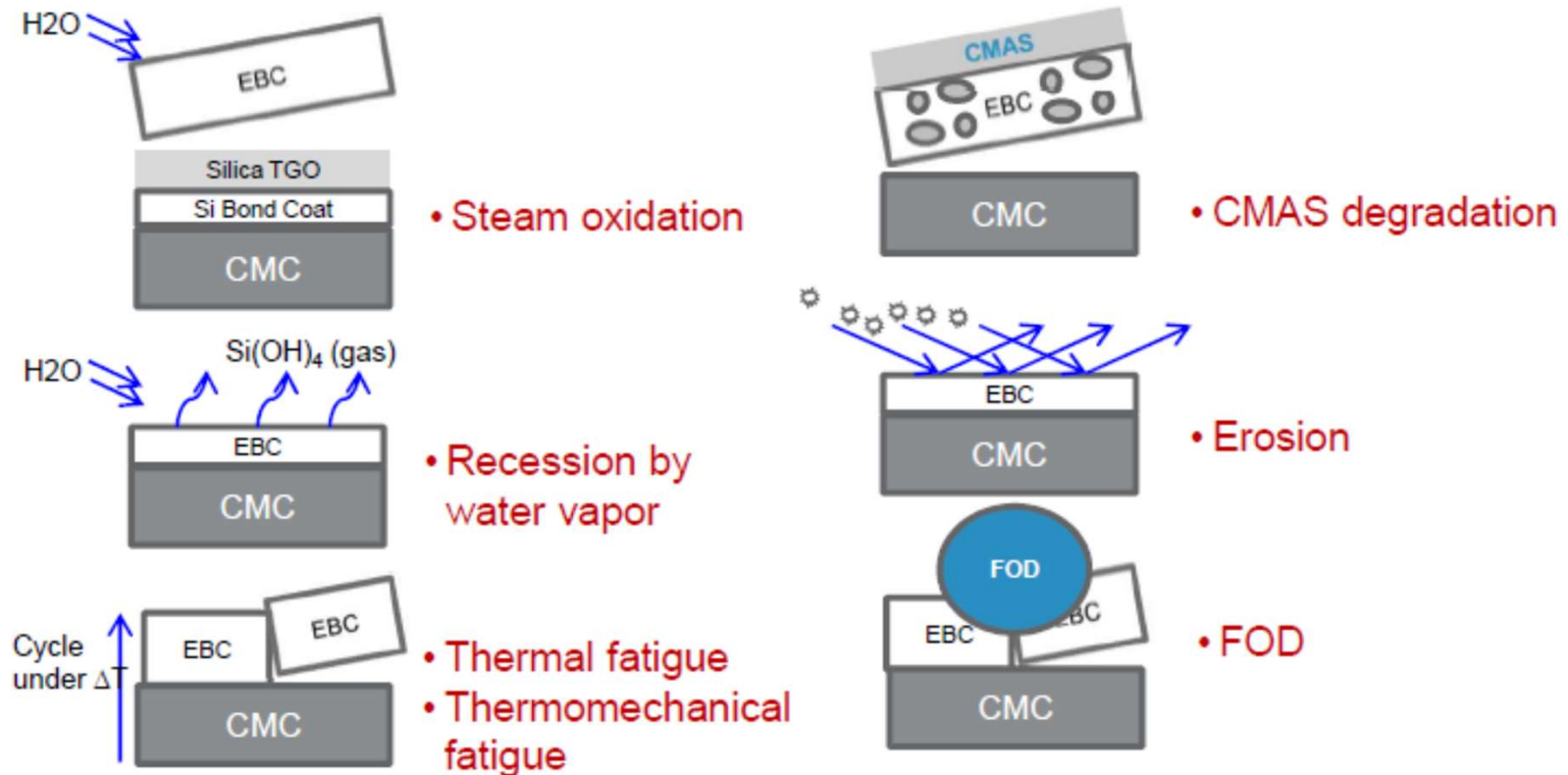
OBSERVATIONS:

- CMAS infiltrated YbDS substrate, suggesting ytterbium disilicate is not effective as a standalone CMAS-resistant EBC
- TEM study revealed no apatite ($\text{Ca}_2\text{Yb}_8(\text{SiO}_4)_6\text{O}_2$) phase formation, supporting results from previous characterization

Contact: Valerie.L.Wiesner@nasa.gov



EBC Failure Modes Investigated



Contact: Ken.K.Lee@nasa.gov



Constituent Development and Characterization

- Engineered matrix for more durable CMC
- Fiber development and testing
- Mini-composites



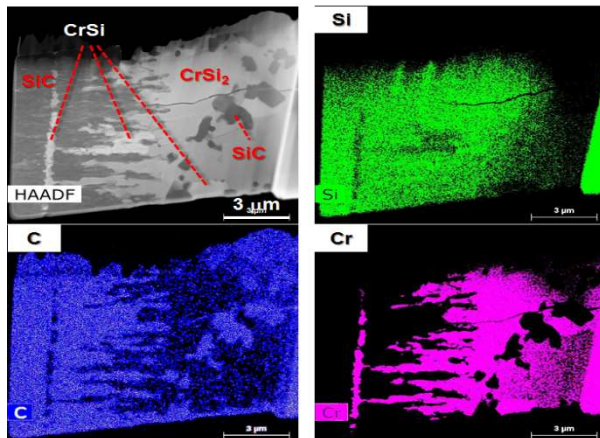
Engineered matrix under development for 2700°F CMC

OBJECTIVE

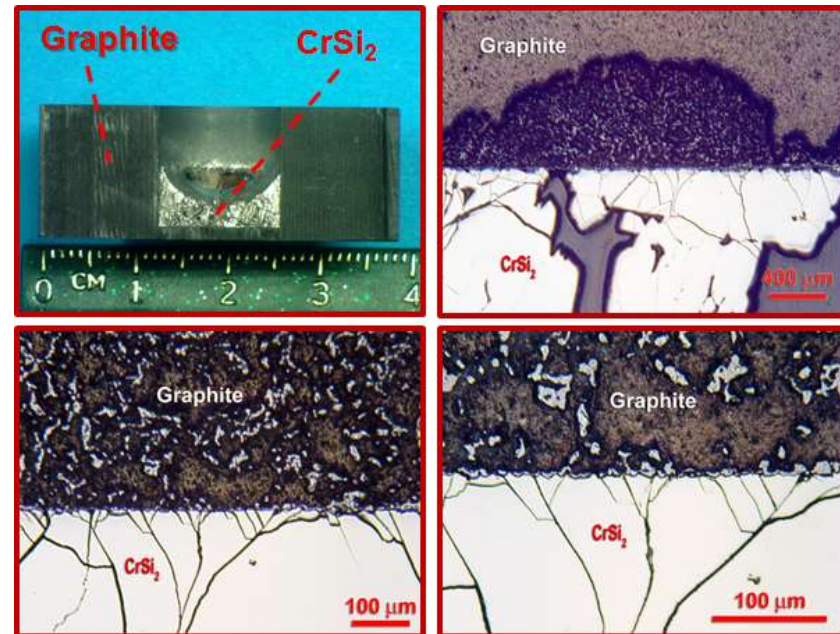
Develop a durable matrix material for CVI SiC/SiC preforms with improved toughness, fatigue life and self-healing properties

APPROACH

- Formulate engineered matrix compositions for evaluation
- Optimize slurry infiltration and melt infiltration (MI) processes to densify CVI SiC/SiC preforms
- Identify optimal matrix composition based on toughness, fatigue life and self-healing properties



NASA / AFRL Collaboration



RESULTS

- High vacuum MI leads to the decomposition of CVI SiC to carbon.
- Carbon reacts with molten CrSi_2 to form SiC.
- In the absence of carbon, CrSi_2 does not react with CVI SiC.
- Pressure melt infiltration is necessary to prevent the decomposition of CVI SiC and the subsequent reaction of molten CrSi_2 with the residual carbon.





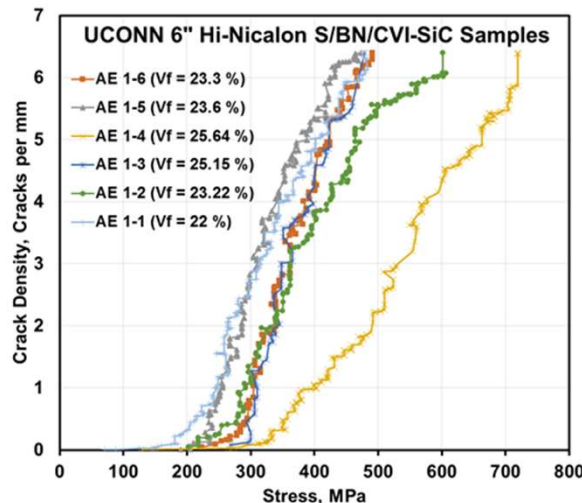
University of Connecticut fabricated SiC / SiC “mini-composites” by Chemical Vapor Infiltration of fiber tows

Objective:

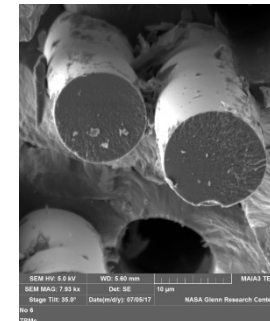
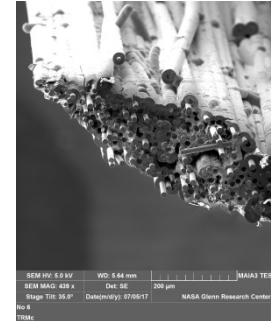
Evaluate uniformity, damage initiation and propagation in minicomposites fabricated at the University of Connecticut

Approach:

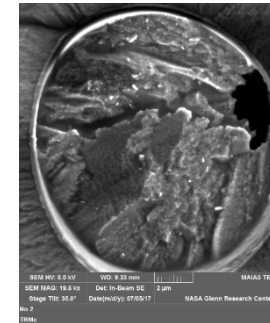
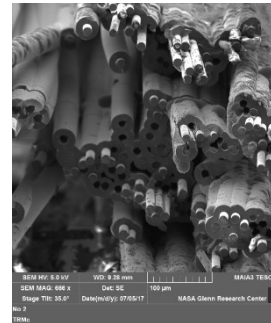
- Use acoustic emission and electrical resistance to estimate matrix cracking stress, damage initiation and progression.
- Compare tensile strength with existing fiber strength data



Results:



HNSUC1-6
 $V_f = 23.3\%$
 $\sigma_f = 2093 \text{ MPa}$
 Low UTS is associated with large fiber's flaw size



HNSUC1-2
 $V_f = 23.22\%$
 $\sigma_f = 2626 \text{ MPa}$
 High UTS is associated with small fiber's flaw size

Summary:

- Mechanical behavior of UConn mini-composites is consistent with existing NASA test data for mini-composites
- Minicomposites will be used for assessment of SiC / SiC environmental degradation

Contact: Amjad.S.Almansour@nasa.gov



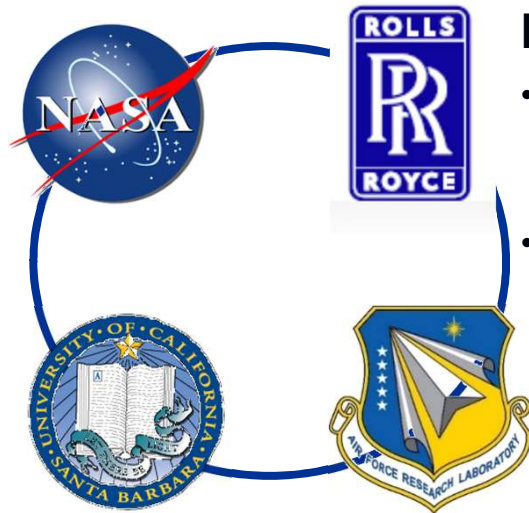
Consortium Established for CMC/EBC Environmental Durability Testing, Modeling & Validation

NASA Glenn

- Conduct mechanical testing of mini-composites at 2200-2700°F in air and steam environments
- Optimize EBC/CMC interface based on bonding and crack deflection
- Develop and validate models for mini-composite properties, durability and failure modes

Univ. California Santa Barbara

- Microstructural characterization of damage progression using Digital Image Correlation, Acoustic Emission measurement and SEM
- NASA Space Technology Research Fellowship



Rolls Royce HTC

- Fabricate CMC mini-composites using industry fabrication processes and constituents
- Define relevant material operating conditions; stress, temperature, environment

Air Force Research Labs

- Damage characterization using Digital Image Correlation and AE methods
- Microstructural characterization by High Energy x-ray imaging (w/ UC Berkeley) and automated serial sectioning of test specimens with data reconstruction

Contact: James.D.Kiser@nasa.gov



CMC / EBC Durability Modeling & Validation

- **Optimization of CMC cooling for maximum durability**
- **Experimental validation of accelerated matrix cracking model in steam environment**
- **Multi-physics model to relate CMC matrix cracking with Electrical Resistance for NDE applications**



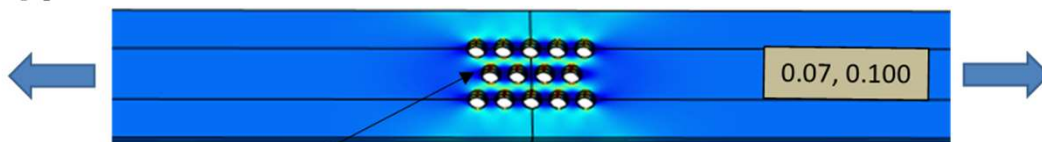
Effects of Cooling Holes on CMC Durability

Objective: Use finite element analysis and coupon tests to investigate the effects of cooling hole configurations on CMC durability

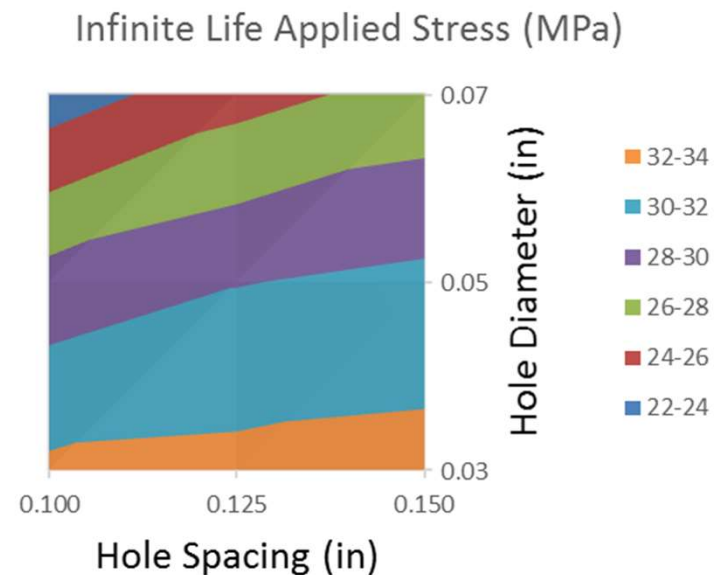
Approach:

- Perform parameter study of effects of cooling hole geometry (spacing, diameter, orientation) on CMC fatigue life using finite element analysis
- Conduct fatigue tests to verify model predictions
- Minimize combined thermal & mechanical stresses for maximum durability of cooled CMC

$$\sigma_{\text{applied}} = 22.9 \text{ MPa (3.3 ksi)}$$



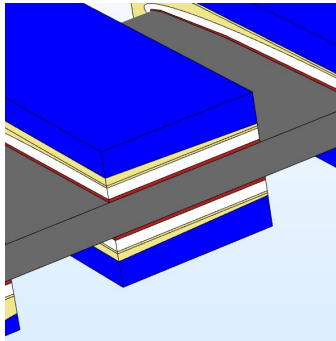
Fatigue tests will be used to verify CMC life prediction model in 2018



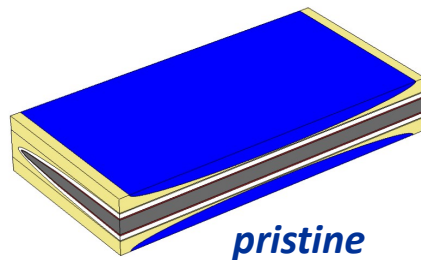
Contact: Roy.M.Sullivan@nasa.gov



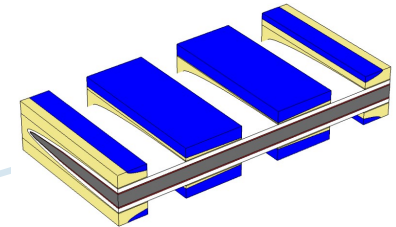
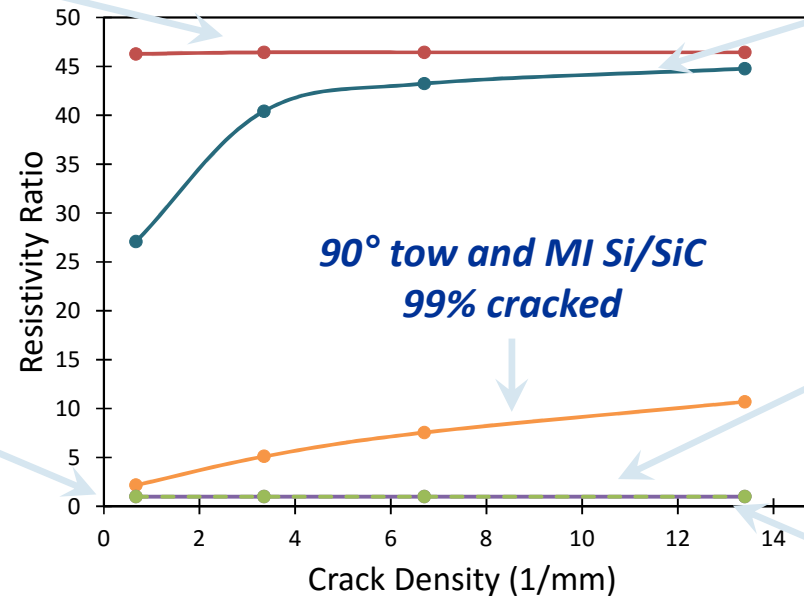
Finite Element Analysis of unit cell with idealized damage states



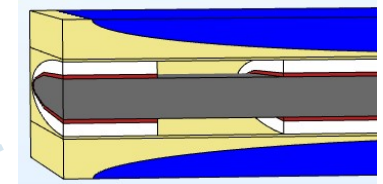
cracks bridged by fibers



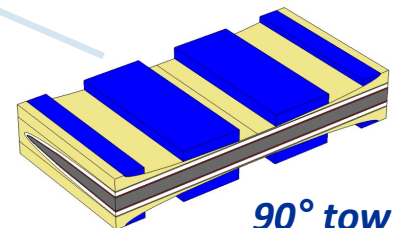
pristine



90° tow and MI Si/SiC cracked



SiC and BN cracked in 0° tow



90° tow cracked

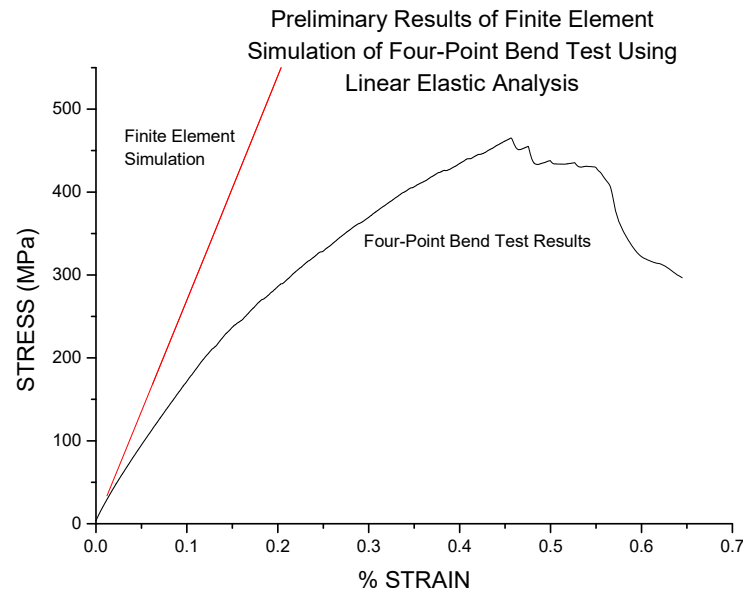
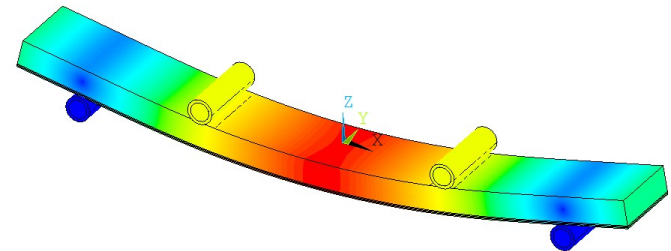
Observations:

- Cracking within 0° or 90° tows has insignificant effect on resistivity
- Cracking of MI Si/SiC matrix has the most significant effect on resistivity



Modeling effects of steam environment on CMC durability & failure modes

Finite Element analysis of CMC/EBC deformation under flexural loading without damage effects. Calculated strength and displacement were comparable with measured values



Results will serve as the baseline to assess effects of steam on CMC/EBC fatigue life



Additive Manufacturing

- **Modified “Binder Jet” process for ceramics and CMCs**
- **Direct Printing for motor components**



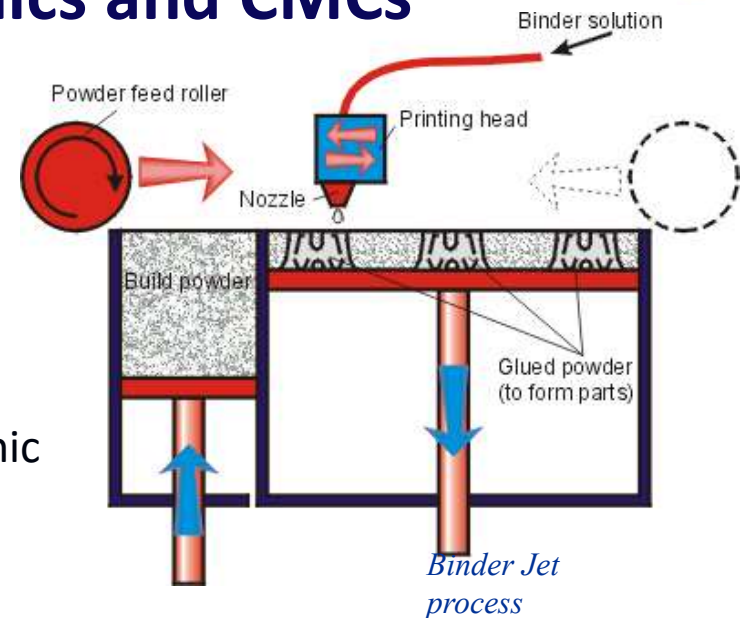
Additive Manufacturing of Ceramics and CMCs

Objective

Accelerate the fabrication, testing & process optimization for CMC fabrication at reduced cost

Approach

- Modify a binder jet machine to fabricate monolithic SiC and SiC CMC
- Characterize the effect of fabrication process parameters and powder composition on microstructure and mechanical properties
- Demonstrate dense monolithic SiC before progressing to chopped-fiber CMC



Benefit

Additive manufacturing of thermally conductive SiC could enable low cost fabrication of lightweight heat exchangers for high power density propulsion systems

Contact: Craig.E.Smith@nasa.gov



Additive Manufacturing for electric motor fabrication

Objective: Use additive manufacturing methods to build more efficient, higher power density electric motors

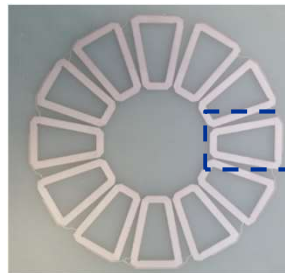
Approach: AM is enabling compact motor designs with lightweight structures, innovative cooling, high copper fill, and multi-material components



Axial Flux Machine – pancake motor



Distributed electric propulsion concept



Higher Electrical Conductivity Coils

Production Benefits: AM eliminates extensive machining, expensive tooling and design changes and high labor cost of conventional manufacturing.

Team members: NASA (GRC, LaRC, ARC) LaunchPoint Technologies and University of Texas - El Paso

Improved air flow
for better thermal
management



Lightweight structures



NASA GRC Focus in 2018

CMC / EBC Durability Modeling & Validation

- Measure effects of environment (steam, CMAS) and cooling holes on CMC durability
- Complete turbine rig test evaluation of 2700°F CMC / EBC
- Validate CMC creep model at 2700°F with mini-composite tests
- Validate SiC fiber crack growth model for CMC rupture life prediction

Additive Manufacturing

- Optimize “binder jet” process for dense SiC and chopped-fiber CMC’s
- Demonstrate Direct Printing for lightweight electric motor components and measure power density improvement in motor tests



Support for CMC research comes from these NASA programs:

Advanced Air Vehicles Program

- Advanced Air Transport Technology Project

Transformative Aeronautics Concepts Program

- Transformational Tools & Technologies Project
- Convergent Aeronautics Solutions Project